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Life cycle assessment of the sugarcane bagasse electricity generation in Brazil

Diogo Aparecido Lopes Silva [a], Ivete Delai [b,c,*], Mary Laura Delgado Montes [a], Aldo Roberto Ometto [a]

[a] School of Engineering of Sao Carlos, The University of Sao Paulo, 400 Trabalhador Sao-carlense Avenue, Sao Carlos 13566-590, Brazil
[b] School of Economics, Business and Accounting of Ribeirao Preto, The University of Sao Paulo, 3900 Bandeirantes Avenue, Ribeirao Preto 14040-900, Brazil
[c] Department of Production Engineering, Federal University of Sao Carlos, Km 235, Washington Luís Road, Sao Carlos 13565-905, Brazil

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A B S T R A C T

This paper aims to identify and quantify the main potential environmental impacts of the sugarcane bagasse electricity generation in Brazil. To do so, it was employed the Life Cycle Assessment (LCA) technique based on primary and secondary data from three previous studies encompassing electricity generation, transmission and distribution processes. It was identified that the main impact potentials of this type of electricity generation in Brazil that should be addressed by decision-makers are the photochemical ozone, the human toxicity via soil and the nutrient enrichment ones, which are caused mainly by the sugarcane straw burning prior harvesting and the chemical application. In addition, it was found that non-renewable resources, renewable resources and energy consumption are also important issues that should be addressed mostly in the process of electricity transmission.

Contents

* Corresponding author at: Federal University of Sao Carlos, Department of Production Engineering, Km 235, Washington Luís Road, 13565-905 São Carlos, São Paulo, Brazil. Fax: +55 16 3351 9517.
E-mail address: ivetedelai@yahoo.com.br (I. Delai).

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1. Introduction

The use of biomass as a source of energy has increased sharply in recent years positioning it as an important energy source in countries such as the United States of America, Germany, Brazil and Japan [1]. The popularity of this organic plant derived material comes mainly from its economic and environmental benefits [2] since it can be easily converted into energy for direct heating applications and/or electricity generation systems [1].

Among several sources of biomass residues that can be employed in energy generation, the sugarcane bagasse is one of the most used in the world. Sugarcane is a tall grass with big stems [3], which is largely grown in tropical countries such as Brazil. The sugarcane bagasse is a by-product of the ethanol and/or sugar production composed mostly of fiber and water and generated in the sugarcane milling process [4]. According to Botha and Blottnitz [5], the bagasse is a residue applied as input resource in 80 sugarcane producing countries, especially for electricity generation.

In Brazil, the electricity generation from bagasse has continuously increased its importance. In 2010, there were 314 power plants generating 6022 MW of electricity from bagasse turning it the third electricity source in terms of capacity [6]. Moreover, Brazilian government's projections show an increase of 65% in the electricity to be exported to the country's grid in 2019 in comparison to 2010 [7]. This situation is not a surprise since Brazil is the largest sugarcane producer in the world [8], with the quantity of sugarcane processed continuing to grow annually [9], and the economic and environmental benefits that it brings to sugar and ethanol industry. The energy production from bagasse is very sound economically since it supplies the whole energetic requirements of the ethanol and sugar production processes as well as it produces an energy surplus that can be sold to the grid. On the other hand, from an environmental point of view, it gives a destiny to a by-product or residue of the industrial process – the bagasse.

Despite being based on renewable resources, the sugarcane industry is not free from environmental impacts mainly when it is assessed from a life cycle perspective. Ramjeawon [10] highlights that electricity generation from bagasse, in the case of Mauritius, brings a lot of environmental benefits when compared to fossil fuels. However, it is a source of renewable energy to some extent because fossil fuels are heavily used in its life cycle. In this sense, several researchers have applied the Life Cycle Assessment (LCA) methodology to evaluate the environmental life cycle impact potentials of sugar and ethanol. A literature review carried out by the authors, detailed in Section 2.3, identified 23 LCA studies of sugarcane products published between 2009 and April 2013. The majority of them focusing on identifying the main ethanol environmental impacts mainly from Brazilian and Dutch researchers.

However, the same cannot be said about energy production from bagasse. The environmental impact potentials of this kind of energy have been little discussed, only 8 studies were identified. Some examples are the researches carried out by Kiatkittipong et al. [11], Pérez Gil et al. [12] and Mashoko et al. [13]. Kiatkittipong et al. [11] presented a model based on the application of LCA to evaluate the environmental impacts of various technologies for dealing with bagasse waste. Pérez Gil et al. [12] evaluated and compared the environmental impacts of different cogeneration technologies currently used in the Cuban sugar industry. Mashoko et al. [13] provided life cycle inventories for the bagasse energy production in South Africa.

No LCA study was found analyzing the whole bagasse electricity cogeneration processes – from production to transmission and distribution to customers – nor the electricity cogeneration in the Brazilian case. Thus, this paper intends to fill this gap by identifying, quantifying and highlighting the main potential environmental impacts of the sugarcane bagasse electricity life cycle in Brazil from production to distribution to customers. This paper is organized as follows. First, Section 2 explains the sugarcane industry's residues and the types of processes and technologies employed for cogeneration, and it reviews the main LCA studies that focused on assessing the environmental impacts of the sugarcane industry's products. Then, Section 3 presents the method employed to carry this research out along with the explanation of the characteristics of the product system studied and assumptions taken. In Section 4, the environmental impact potentials are presented and discussed and, finally, Section 5 draws the conclusions.

2. Literature review

2.1. Residues of the sugarcane industry

The production of sugar and ethanol, from a cradle-to-gate approach, generates two main types of residues – agricultural waste and industrial by-products. The first group is composed mostly of the sugarcane straw that is burned or milled in the harvesting process. On the other hand, the industrial processes generate five main types of residues or by-products – ash, bagasse, filter cake, molasses and vinasse – which can be recycled and/or sold as co-products as shown in Fig. 1.

- *Ash*: it is often generated during the energy cogeneration process in bagasse boilers and can be applied as fertilizer in agricultural activities;
- *Filter cake*: it is an organic waste from the mill's filtration process where the juice is extracted in rotary filters. The cake is commonly employed as fertilizer, but it can also be applied to produce biogas via anaerobic digestion processes [3].
- *Molasses*: it is a by-product of the centrifugation process during sugar production that can be used as animal food and/or as resource for ethanol production [14].

- *Vinasse* (*or waste water*): it is a co-product of the alcohol distillation process that can be used with the filter cake to produce biogas or be recycled to the field [15] as fertilizer (ferti-irrigation).
- *Bagasse*: it is the most important solid by-product from sugarcane, generated during the sugarcane juice extraction process [11]. Typically the moisture content of bagasse is 40–50%, and its major chemical components are [16] cellulose (30.0%), hemicelluloses (23%) and lignin (22%). It represents around half of the sugarcane matter and is strongly intermeshed in lignocelluloses [17].

The bagasse is one of the biomass residues most applied to energy generation in the world. According to Botha and Blottnitz (2006), the bagasse is a residue applied as input resource in 80 sugarcane producing countries, especially for electricity generation. This popularity is due to the economic and environmental benefits that it brings to the sugar and ethanol industry. The energy production from bagasse is very sound economically since it supplies the whole energetic requirements of the ethanol and sugar production processes as well as it produces an energy surplus that can be sold to the grid. From an environmental point of view, it gives a destiny to a by-product or residue of the industrial process. Several worldwide reports have pointed out the benefits of utilizing bagasse for cogeneration as a part of grid electricity – Cuba [12], India [18], South Africa [13], United States of America [19] –and also its sustainability benefits [1]. In addition, Kiatkittipong et al. [11] highlight that bagasse energy cogeneration is still conventional because of its economic feasibility and environmental advantages [20] compared to fossil fuels.

The bagasse can also be used in several other applications such as to produce pulp and paper products, building materials and second generation biofuels [21,22].

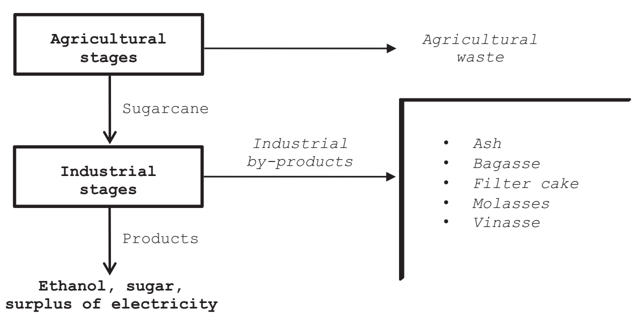

Fig. 1. Products and by-products of the sugarcane industry.

2.2. Electric energy production in cogeneration systems

Biomass can be converted into energy via three main types of processes: physical, thermo-chemical and biological [23] – as illustrated in Fig. 2. According to Goldemberg et al. [24], Lee et al. [25] and Naika et al. [26], these three groups of processes can be summarized as follows:

- *Physical conversion*: it consists of a set of physical modification processes of biomass (i.e. wood and other vegetables), such as cutting, breaking, sorting, pressing, drying or compressing the solid biomass, to obtain a final product (i.e. pellets, briquettes, shaves). It can also include mechanical extraction processes such as the ones employed to produce biofluids (vegetable oils);
- *Thermo-chemical conversion*: it is applied to any kind of biomass (wood and non-wood plants, organic waste and biofluids) and it includes four techniques – direct combustion, gasification, liquefaction and pyrolysis with or without physical conversion. Direct combustion, the most popular technique, is the transformation of a fuel's chemical energy into heat by means of the complete oxidation of solid biomass in excess air generating carbon dioxide and water. Gasification is a process that converts solid fuel in gas (mixture of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen) through thermo-chemical reactions involving hot steam and air or oxygen in

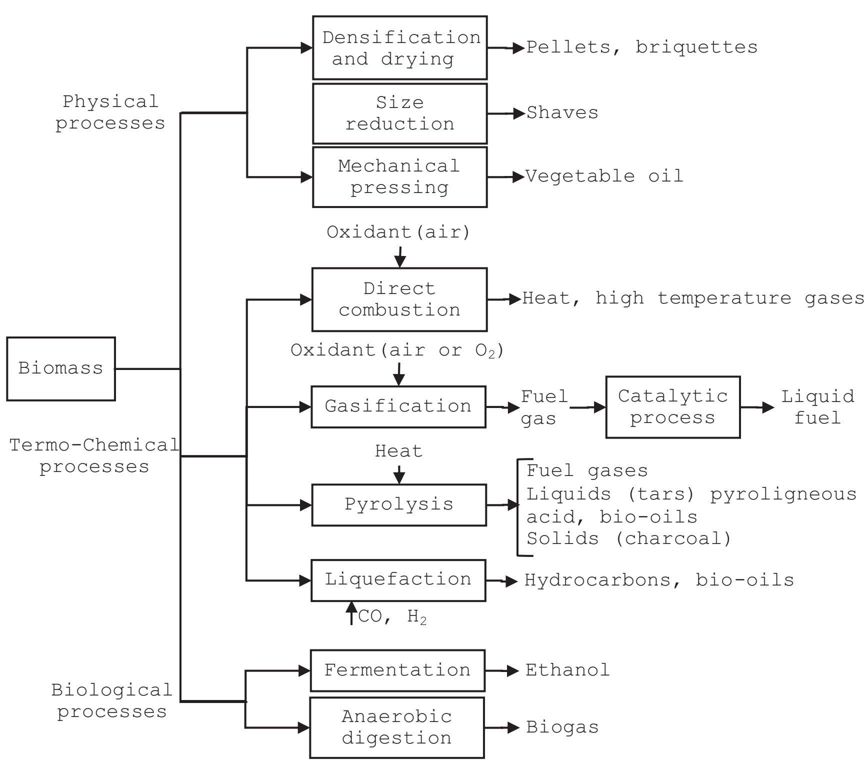

Fig. 2. The routes of biomass energy conversion.
Source: Lora and Andrade [23].

amounts lesser than the stoichiometric. Liquefaction is the production of liquid fuels by means of the reaction of crushed biomass (wood and agricultural residues) in a liquid medium with carbon monoxide in the presence of an alkaline catalyst. Pyrolysis or carbonization is the simplest and oldest process of fuel conversion (i.e. wood and agricultural waste) in another one of better quality and energy content (coal, essentially), generating gas fuels such as tar and pyroligneous acid.

- *Biological conversion*: it comprises biodigestion and alcoholic fermentation technologies, which are commonly applied to conversion of urban and agro-industrial organic residues and non-wood vegetables in their liquid state at low concentrations. The main product of biodigestion is the biogas obtained from the conversion of the organic waste energy, which is composed mainly of methane and carbon dioxide. In the case of alcoholic fermentation, sugar plants (e.g. sugarcane) are converted into alcohol through the action of microorganisms (e.g. yeast) producing ethanol.

In the case of the electricity generation, thermo-chemical processes are very common [1]. Direct combustion is the oldest and simplest thermo-chemical biomass conversion technology being very popular in energy cogeneration systems in general [27] as well as in the sugarcane bagasse electricity cogeneration case. Despite being less efficient than gasification and pyrolysis, direct combustion is usually employed in the sugarcane industry because it requires significantly less investment and process control.

Cogeneration is a process of producing both electricity and usable thermal energy. Bain et al. [27] explain that the cogeneration process follows the Rankine Cycle, and that the high temperature gases from the biomass combustion are used to generate steam that drives a turbine producing electricity. A general scheme of how the biomass energy cogeneration occurs in the sugarcane industry is summarized in Fig. 3 and explained below.

In the cogeneration plant, the most employed system encompasses a steam boiler and a back-pressure steam turbine (or a turbogenerator). The combustion of biomass occurs in the industrial boilers fed by the bagasse and water for steam generation process. A fossil fuel (i.e. diesel, heavy oil) can also be used in the process as auxiliary for combustion. The live steam supplies the back-pressure turbine, which drives a generator for electrical power generation. The steam leaving the turbine flows into heating equipments (e.g. mill drives) in the industrial stages of sugar/ethanol production [28,29].

It is well-known that the main parameters of a cogeneration system are steam pressure and temperature [29] which directly affect the efficiency of boilers and the production of electricity surplus. Higher temperature and pressure can provide higher levels of net power from bagasse. Table 1 shows how these parameters affect the

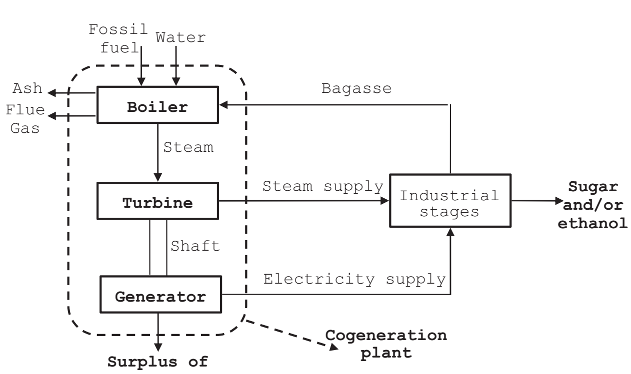

Fig. 3. General layout of a cogeneration plant in the sugarcane industry.
Source: Adapted from Chauhan et al. [14].

Table 1
Electric power and bagasse surplus in cogeneration systems.
Source: Adapted from MECAS [28].

Cogeneration systems parameters	Electric power surplus (kg/tc)	Bagasse surplus (kg/tc)
21 bar, 300 °C	10.4	33
42 bar, 400 °C	35.4	50
42 bar, 450 °C	28.3	48
65 bar, 480 °C	57.6	13

tc – ton of sugarcane.

production of energy surplus in the sugarcane industry. The following conditions were assumed: the production of 280 kg of bagasse (with moisture content of 50%) per ton of sugarcane (tc), the use of back-pressure steam turbines, the consumption of steam of 500 kg/tc; and process steam pressure at 2.5 bar. There is a consensus that 1 t of sugarcane processed yields 250–280 kg of bagasse (with moisture content of 50%), which can produce 500–600 kg of steam, and that around 400–600 kg of the steam generated are consumed in the sugar/ethanol production processes [30,28,31].

In this sense, in order to maximize the amount of electricity surplus sold to the grid, it is essential the adoption of energy conservation approaches. Some examples are the use of energy-efficient motors and pumps and, mainly, the use of more efficient high pressure boilers in combination with condensing extraction steam turbines [30]. Such approaches reduce the use of steam and power by the production processes because depending on the boiler specifications it is possible to change some features of the steam generation [12].

Nowadays in Brazil, most parts of the sugarcane mills operate at pressures of 22 bar [32]. However, the new generation of high-efficiency boilers being installed on grid-connected bagasse cogeneration plants can produce extra-high pressures and temperatures. For instance, BNDES/CGEE [30] built a plant that operates generating steam at 105 bar and 525 °C that reduced process steam demand to 280 kg/tc.

2.3. Life Cycle Assessment (LCA) of sugarcane bagasse electricity generation

LCA is a technique that identifies and evaluates inflows and outflows of materials and energy as well as potential environmental impacts of a product system throughout its life cycle [33]. It has proved itself useful as an approach for identifying hotspots and opportunities to improve environmental aspects of products at several points of their life cycles [34]. These environmental improvements promote cost savings, by reducing the generation of waste and rationalizing the use of resources, as well as brand and reputation benefits.

According to the ISO 14040 e 14044 standards, a LCA study encompasses four main phases, as shown in Fig. 4: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation [33]. Each of these phases is explained in Section 3 along with the specific aspects and scope of the study presented in this paper.

According to the literature review[1] carried out by the authors, summarized in Table 2, the LCA of the sugarcane bagasse electricity generation is very little discussed in the extant literature. Amongst the 23 LCA studies identified published between 2009 and 2013, the majority focused on the quantification of the environmental impacts

[1] It was searched papers published between January 2009 and April 2013 in Journals indexed by the Web of Knowledge. The expressions searched in the articles' title and keywords were: LCA and electricity; LCA and sugar; LCA and ethanol.

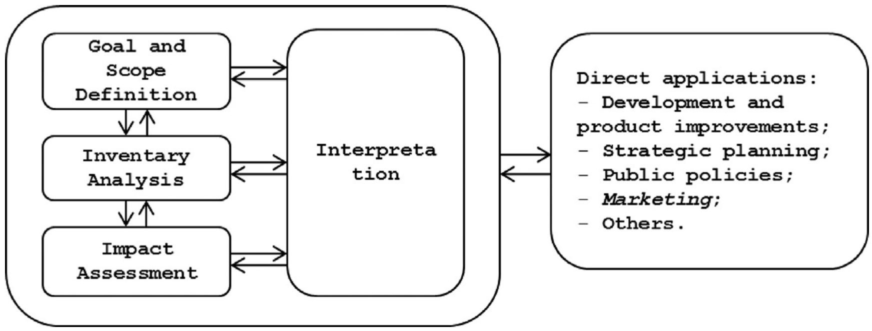

Fig. 4. Phases of LCA study according to the ISO 14040 standard.
Source: Adapted from ISO [33].

of ethanol (12 publications), identifying hotspots, analyzing opportunities of improvement and presenting comparative scenarios with fossil fuels. Only four papers analyzed electricity generation itself and other four assessed it together with sugar and/or ethanol productions. In terms of country of origin, most part are from Brazil (4 publications), Netherlands (4 publications), Thailand (3 publications) and South Africa (3 publications).

Regarding their purposes and methods, it can be said that the majority (13 publications) present similar objectives – identifying hotspots and opportunities for improvements – however they pursuit it employing different methods, mainly IPCC – Intergovernmental Panel on Climate Change (6 publications), GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation – (4 publications) and Eco-indicator 99 (3 publications). This lack of standard method hinders the process of establishing a common knowledge about the main environmental impacts of the ethanol, sugar and/or electricity generation processes. This situation is even worse in the case of electricity LCA's, since each study employed different methods to assess the environmental impact potentials such as energy consumption/balance, emergy analysis, and LCIA methods application (GREET, IMPACT2002+, Eco-indicator 99 and EDIP 97).

Finally, it is important to note that no electricity cogeneration study was found that analyzed the Brazilian case nor the electricity transmission and distribution phases.

3. Material and methods

This study applies the LCA technique based on the ISO 14040 series standard in order to achieve its objectives. According to this standard, a LCA study encompasses four main phases as shown in Fig. 4, which are detailed below according to the specific considerations of this study.

3.1. Goal and scope definition

This phase aims to define the objective of the LCA study alongside the product system boundaries [33]. The first one establishes the intended application or use of the study, the reasons for its development and its target public, while the second one encompasses mainly the studied product system, the system function, the functional unit and the system boundaries and limitations.

3.1.1. Goal of the study

The aim of this study is to identify and quantify the potential environmental impacts of the bagasse electricity generation system to identify its main improvement opportunities. It intends to support both ethanol industry and governmental decision making processes to minimize the environmental impact of this type of energy generation. The first group will find it useful to identify opportunities to improve the environmental performance of the sugarcane bagasse energy generation process, while the second one could establish more specific, focused and effective regulations to address the main impact potentials.

3.1.2. Scope of the study

3.1.2.1. Product system function. A system function is described as the purpose of the product or service analyzed [33]. In this study, the service focused is the electricity generated from bagasse in three sugarcane plants in the Northeast of São Paulo State (Brazil), transmitted and distributed to customers. And the function analyzed is the generation of an amount of electricity surplus that can be sold to the Brazilian's grid after supplying the energy demand of the ethanol production processes, its transmission and distribution to customers.

3.1.2.2. Functional unit and reference flow. The functional unit quantifies the outputs of the system function in focus providing a reference to which the inputs and outputs of the system can be related to. The reference flow quantifies the part of the product studied that is necessary to perform the function defined by the functional unit [33].

In this study it was necessary to consider two functional units since it was developed based on three studies that employed different functional units. Thus, the functional units and the reference flows for this LCA are as follows:

- Electricity generation surplus of 1 MW h (processes 1–7);
- Electricity transmission and distribution of 1 MW h km (processes 8 and 9).

3.1.2.3. Product system boundaries and limitations. This part defines the set of processes of the studied product system that will be considered in the LCA. In this study, the product system encompasses nine process described as follows (Fig. 5):

1. *Soil preparation* (1): encompasses agricultural operations to improve physical, chemical and biological conditions of the soil for seeds germination;
2. *Sugarcane plantation* (2): it is carried out mainly manually where sugarcane pieces are laid in trenches. Several equipments are used in this process: trucks to transport sugarcane pieces, tractors to open trenches and to spread some pesticides and buses to transport workers [15];
3. *Chemical application* (3): comprises pesticides and fertilizers application to preserve soil properties and to control pests. Tractors are used to perform these activities [15];
4. *Irrigation* (4): it is the aspersion of vinasse on the sugarcane plantation area alongside some decomposed solid residues. The vinasse is a by-product of the ethanol distillation process

Table 2
LCA studies of sugarcane products – ethanol, sugar and electricity – published between 2009 and 2013.

Product	Country	Ref.	Purpose	Methods	Environmental aspect and impact categories
Electricity	Cuba	[12]	– Identifying hotspots and improvements	*LCIA method:* – Eco-indicator 99	– Acidification/eutrophication – Carcinogens – Climate change – Ecotoxicity – Fossil fuel use – Land use – Minerals use – Ozone layer depletion – Radiation – Respiration – organics and inorganics
Electricity	India	[20]	– Identifying hotspots and improvements	*Literature review*	– Primary energy demand – Greenhouse gas emissions
Electricity	South Africa	[13]	– Inventory data	*LCI method* – Mass and energy balances	– Fossil energy consumption – Carbon dioxide emissions – Methane emissions – Nitrous oxides emissions – Sulfur dioxide emissions
Electricity	Thailand	[11]	– Evaluating alternative pathways to produce electricity	*LCIA method:* – EDIP 97	– Acidification – Global warming – Eutrophication – Photochemical oxidant creation
Ethanol	Brazil	[35]	– Identifying hotspots and improvements	*Energy analysis*: – Emergy analysis – Fossil fuel embodied energy	– Transformity – Renewability – Emergy yield ratio – Environmental loading ration – Emergy sustainability index – Emergy exchange ratio
Ethanol	Brazil	[15]	– Identifying hotspots and improvements	*LCIA method:* – EDIP 97	– Acidification – Global warming – Ozone formation – Nutrient enrichment – Ecotoxicity – Human toxicity
Ethanol	Netherlands	[36]	– Comparing a range of biofuels	*LCIA method:* – IPCC	– Global warming – Land use
Ethanol	United States	[37]	– Inventory data	*LCIA method:* – GREET	– Global warming
Ethanol	Netherlands	[38]	– Comparing the impacts as gasoline and ethanol as fuels	*LCIA method:* – CML 2	– Abiotic depletion – Acidification – Eutrophication – Greenhouse gas emissions – Ozone layer depletion – Photochemical oxidation – Human and ecotoxicity
Ethanol	Brazil	[39]	– Identifying hotspots and improvements	*LCIA method:* – GREET	– Greenhouse gas emissions
Ethanol	Mexico	[40]	– Identifying hotspots and improvements	*LCIA method:* – IPCC	– Greenhouse gas emissions – Land use
Ethanol	Sweden	[41]	– Comparing with fossil fuels	*LCIA method:* – IPCC	– Greenhouse gas emissions
Ethanol	Netherlands	[42]	– Identifying hotspots and improvements	*LCIA method:* – IPCC	– Greenhouse gas emissions

Table 2 (*continued*)

Product	Country	Ref.	Purpose	Methods	Environmental aspect and impact categories
Ethanol	Netherlands	[43]	– Identifying hotspots and improvements	*Literature review*	– Acidification – Biodiversity – Eutrophication – Global warming – Land use – Net energy output – Toxicity – Water use
Ethanol	Thailand	[44]	– Comparing ethanol from molasses and cassava – Identifying hotspots and improvements	*Energy analysis:* – Net energy balance – *LCIA method:* – CML 2	– Net energy ratio – Renewability – Acidification – Eutrophication – Global warming – Land use – Photochemical oxidation
Ethanol	United Kingdom	[22]	– Identifying hotspots and improvements	*Literature review*	– Acidification – Ecotoxicity and human health – Energy consumption – Eutrophication – Greenhouse gas emissions – Water consumption
Ethanol, Sugar, **Electricity**	Brazil	[32]	– Identifying hotspots and improvements	*LCIA method:* – GREET	– Energy use – Greenhouse gas emissions
Ethanol, Sugar, **Electricity**	Australia	[45]	– Comparing bioenergy, biofuel and biomaterial productions – Examining methodological considerations	*LCIA method:* – Impact 2002+	– Acidification – Eutrophication – Global-warming – Land use – Non-renewable energy use – Respiratory inorganics – Respiratory organics – Water use
Ethanol, **electricity**	United States	[46]	– Evaluating alternative pathways to produce electricity and ethanol	*LCIA method:* – GREET	– Greenhouse gas emissions – Land use
Ethanol, **electricity**	South Africa	[21]	– Comparing cellulosic ethanol with bagasse electricity cogeneration	*LCIA method:* – Impact 2002+	– Acidification – Global warming – Non-renewable energy use – Eutrophication
Sugar	Cuba	[3]	– Comparing alternative uses for sugar milling by-products and wastes	*LCIA method:* – Eco-indicator 99	– Acidification/eutrophication – Carcinogens – Climate change – Ecotoxicity – Fossil fuel use – Land use – Minerals use – Ozone layer depletion – Radiation – Respiration – organics e – Respiration – inorganics
Sugar	South Africa	[13]	– Identifying hotspots and improvements	*LCIA method:* – Eco-indicator 99	– Acidification/eutrophication – Carcinogens – Climate change – Ecotoxicity – Fossil fuel use – Land use – Minerals use – Ozone layer depletion – Radiation – Respiration – organics e – Respiration – inorganics
Sugar	Thailand	[47]	– Estimating carbon footprint of sugar production	*LCIA method:* – IPCC	– Global warming

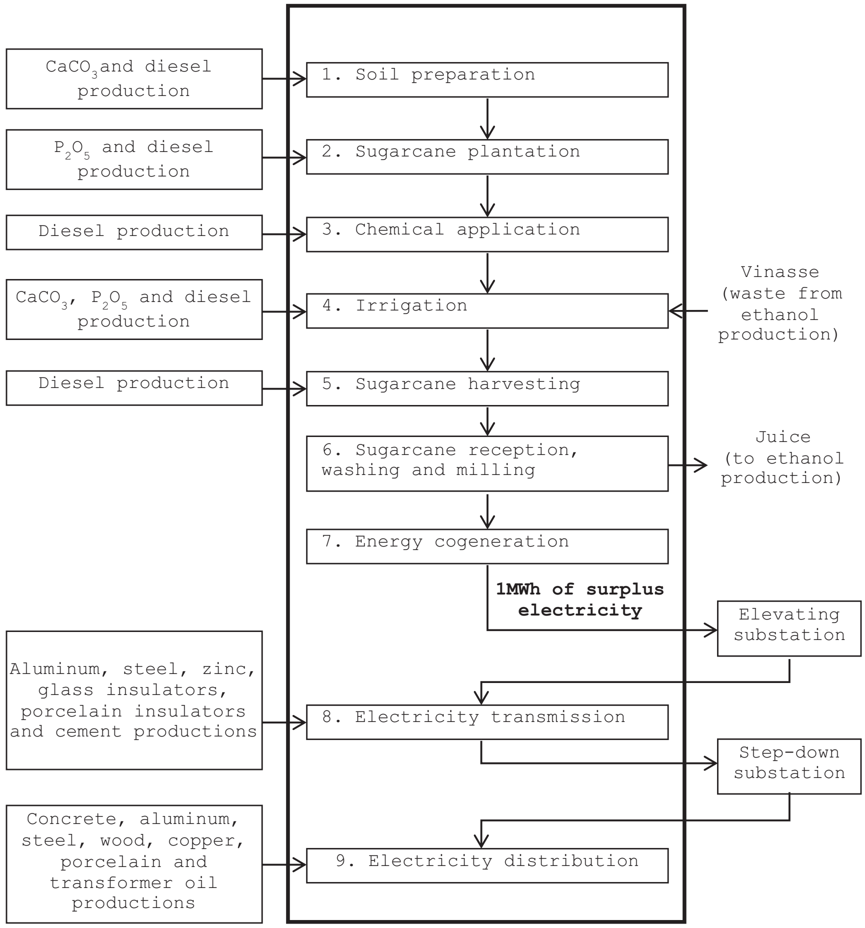

Fig. 5. Product system boundaries of the sugarcane bagasse electricity generation studied.

rich in nutrients [15] that can replace fertilizers in the soil preparation;

5. *Harvesting* (5): this process can be performed in four ways: manual harvesting with prior sugarcane straw burning; manual harvesting of green sugarcane; mechanical harvesting with prior sugarcane straw burning; and mechanical harvesting of green sugarcane [48]. Harvesting in the studied case is carried out mostly manually with prior sugarcane straw burning in 75% of the area [15]. After harvesting, sugarcane is transported to production plants by trucks;
6. *Sugarcane reception, washing and milling* (6): these are the initial phases of the industrial process where sugarcane fibers and juice are separated. A mill washes, chops, and uses revolving knives to shred the sugarcane. Shredded sugarcane is repeatedly mixed with water and crushed between rollers. The juice extracted flows to the ethanol production processes and the fibers, or bagasse, go to the energy generation processes;
7. *Energy cogeneration* (7): the bagasse is burned in a boiler and the thermal energy produced is used for steam generation. This steam is expanded in turbines to power the plant's mechanical equipments and to generate electricity, which will be exported to the grid;
8. *Electricity transmission* (8): the electricity generated in the seventh process flows to an elevating substation close to the plant that adequate the electricity voltage to be transmitted via transmission lines to a step-down station;
9. *Electricity distribution* (9): the electricity is taken from a step-down station (tension ranging from 2.3 to 34.5 kV) to consumers (tensions between 110 and 380 V).

3.1.2.4. Key assumptions. Several key assumptions were taken into account in this study as follows:

- The data for processes 1–7 relates to an autonomous distillery that produces only ethanol, which was obtained from a previous ethanol life cycle assessment carried out by Ometto [49]. It is important to highlight that this previous study evaluated the potential environmental impacts of the ethanol production process, the impacts of the calcium carbonate ($CaCO_3$) extraction, the production of phosphorous fertilizer (P_2O_5) and diesel as well as transport operations as shown in Fig. 5;
- The original inputs and outputs data of process 6 (sugarcane reception, washing and milling) collected from Ometto [49] needed to be divided, since this is a shared process between the ethanol and the electricity productions, thus, its impacts must be also shared between these two products. In order to do it, it was collected primary data of the bagasse production in the industrial processes from an autonomous distillery that shown that 50% of the bagasse is consumed by process unit 6 to generate electrical and thermal energy and 50% by the ethanol production processes. Thus, only 50% of the ethanol industrial process potential impacts from the original data were considered in the process 6;
- The data for process 8 was acquired from a secondary source [50] regarding a transmission line of 138 kV, which is the most popular line in Brazil and in the studied distillery surroundings. It is worth to notice that this process secondary data encompasses the impacts of the transmission components, their material production, the lines construction and operation and that the impacts of the line maintenance and decommissioning processes were disregarded. Thus, in the transmission lines′ life

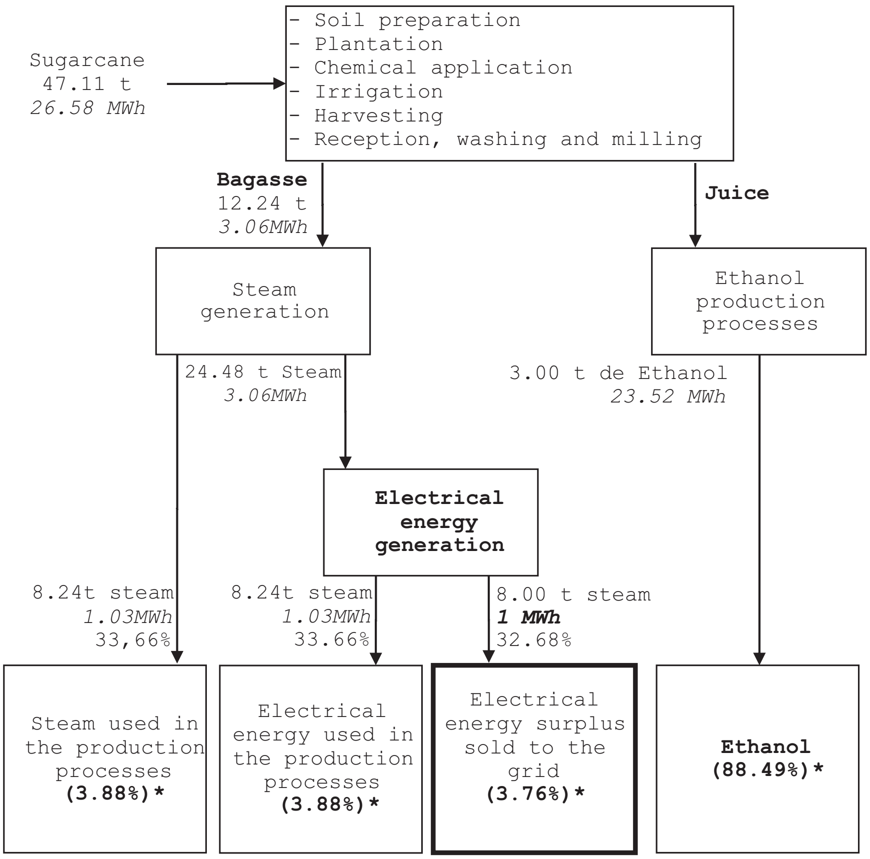

Fig. 6. Material and energy balance of the ethanol/electricity processes.

cycle inventory was considered aluminum, glass and porcelain isolators, concrete, zinc and steel production as shown in Fig. 5;

- The data for process 9 was also collected from a secondary source [51]. It was considered the that impacts of a distribution line of CPFL Energy, a utilities company, are responsible for energy distribution in the surroundings of the sugarcane distilleries studied in this research [52]. It includes the impacts of the distribution lines' components and their material production, lines construction and use. The impacts of the distribution lines maintenance and decommissioning processes were disregarded. Thus, in the distribution lines' life cycle inventory was considered concrete, aluminum, steel, oil for transformer, copper, wood and porcelain productions as shown in Fig. 5;
- It is important to note that substations, both elevating and step-down, were excluded from the product system analyzed.

In addition, since the processes 1–7 were shared by the ethanol production and the bagasse electricity generation, it was necessary to separate the proportion of environmental impacts of each sugarcane product – ethanol and electricity. To do so, it was employed an allocation process based on energetic criteria illustrated in Fig. 6, which presents the material and energy balance to produce 1 MW h of electricity surplus – the functional unit of this study. The following assumptions were considered in the energy balance:

- For didactic purposes, the total energy values were standardized in MW h and written on each node in the flow of Fig. 6;
- 1 t of steam produces 0.125 MW h of electricity [15];
- 2 t of steam are produced by 1 t of bagasse [15];
- 4.085 t of bagasse are produced by 1 t of ethanol [15];
- 1 t of ethanol is produced by 15.72 t of sugarcane [15];
- The heating value of the hydrous ethanol is 28.225 kJ/kg (or 6741.43 kcal/kg) [30];
- Energy losses were not measured.

Based on these assumptions, it can be concluded that in order to produce 1 MW h of electricity surplus is necessary 47.11 t of sugarcane, which produces 3 t of ethanol and 12.24 t of bagasse. The combustion of this amount of bagasse generates 24.48 t of steam (3.06 MW h) whereof 8.24 t (1.03 MWh – 33.66%) are consumed in the sugar and ethanol production processes and the remaining steam (2.03 MWh – 66.34%) is used to generate electrical energy [15]. Part of this electrical energy is consumed by the ethanol industrial processes (1.03 MWh – 33.66% of the total steam generated), while the surplus (1 MW h) is distributed to the grid. In addition to the energy generated by the bagasse, the sugarcane industrial process has also the internal energy of ethanol, which is the product of the process that, in the case, equals to 23.52 MW h.

Based on this information, it can be concluded that 1 MW h of electricity surplus represents only 3.76% of the total sugarcane energy potential (26.58 MWh), thus only this proportion of the environmental impact potential of the ethanol production processes should be allocated to the electricity generation processes: 1–7.

Finally, some considerations can also be drawn regarding to the impact categories employed in the analysis:

- It was considered the global warming and ozone depletion characterization factors for 100 years, photochemical ozone characterization factors for low nitrogen oxides (NO_x), and water and soil ecotoxicity characterization factors for chronic ecotoxicity in water;
- The emissions related to sugarcane were not considered in bagasse electricity life cycle because they come from a renewable source.

Table 3
Sources of secondary data employed in this study.

Element	Ometto [49,15]	Victorino [52]	Yokote [50]
Objective	To assess ethanol life cycle potential environmental impacts	To inventory the life cycle impacts of electricity transmission lines	To inventory the life cycle impacts of electricity distribution lines
Data collection timeframe	2001–2005	2001	1999–2000
Data collection place	Ethanol industry with traditional up-to-date ethanol process technology in the Northeast of São Paulo State (Brazil)	Brazilian electricity transmission lines	Brazilian electricity distribution lines
Cut off criteria	0.34% of the total mass of all inputs consumed in the product system	1% of the total mass of all inputs consumed in the product system	1% of the total mass of all inputs consumed in the product system
Functional unit	10,000 km	1 MW h km transmitted	1 MW h km distributed
Processes	1–7	8	9
Data source	Primary data, SimaPro software and literature	Primary data, SimaPro software and literature	Primary data, SimaPro software and literature
Data lifespan	10 years	25 years	20 years

3.2. Inventory analysis

The life cycle inventory phase encloses data collection and calculation in order to quantify inputs (energy, raw and ancillary materials and other physical inputs) and outputs (products, emissions and waste) of a product system.

The data used to carry out this study was a combination of primary and secondary sources published in three previous LCA studies – Ometto [49], Victorino [52] and Yokote [50]– as shown in Table 3.

Considering the timeframes of the inventory databases of each secondary data source presented in Table 3, it can be said that the data lifespan of this study is 1 year for the electricity generation processes, 12 years for the transmission process and 6 years for the distribution process.

3.3. Impact assessment

The life cycle impact assessment aims to evaluate the significance of the potential environmental impacts via the translation of the inventory results in a set of specific environmental categories and indicators [33]. It encompasses mandatory (environmental impact categories and indicators selection, classification and characterization) and optional elements (normalization and weighting).

In this study, the impact assessment was carried out based on the categories and indicators proposed by the Environmental Design of Industrial Products (EDIP) method [51]. The EDIP method is midpoint and treats the impact categories within three main groups: environmental impacts (emissions and waste), resource consumption (renewable, non-renewable and energy) and impacts on the working environment (risks to employee's health). In this research, the latter category was disregarded since these impacts were not considered by the secondary data sources from which this study was derived.

In addition to the mandatory LCA steps, in order to facilitate the analysis and the identification of hotspots, the results were normalized according to the EDIP method [51]. Normalization is the calculation of the magnitude of each impact category in relation to a standard reference [33], being an optional step for the ISO 14040. “It describes how the relative size of the resource consumptions and the impact potentials are assessed via comparison with a background impact” [51, p. 40] facilitating the identification of key issues to be addressed by decision makers. The background impact in the EDIP Method is expressed as the average impact European EU person per year or person-equivalents (PEw.EU) [51]. This means that the environmental impact potentials of category can be understood as fraction of the annual impact from an average EU citizen. For example, if the global warming's normalized score of a product system is 4.3 PEw.EU, this means that the global warming impact of this system in one year corresponds to the global warming emissions of 4.3 EU citizens in one year. Section 4.4.9 presents the normalized scores of the system assessed in this paper.

3.4. Interpretation

The life cycle interpretation phase aims to draw the main conclusions, recommendations and limitations of the study via the combination of the results of the inventory and impact assessment phases [33]. It must be carried out aligned with the study's objective and scope. The interpretation phase of this study is described and discussed in Section 4.

4. Results

This section presents the potential environmental impacts of the sugarcane bagasse electricity generation, transmission and distribution processes considering their specific functional units (FU) – generation of 1 MW h of surplus electricity, and the transmission and distribution of 1 MW h km of electricity. These impacts are presented in four subsections: consumption of non-renewable resources, consumption of renewable resources, consumption of energy and emissions. Tables are employed to present the amount of resource consumption or emission of each process along with its relative percentage to the total amount identified for each group of processes – electricity generation (group 1) and electricity transmission and distribution (group 2).

4.1. Consumption of non-renewable resources

Table 4 presents the consumption of non-renewable resources of all processes studied. An analysis of the electricity generation processes (processes 1–7) shows that processes 1 (soil preparation) and 3 (chemical application) are responsible for 66% of non-renewable resources consumption in this phase. This is mainly due to the consumption of fertilizers in the agricultural activities.

On the other hand, an analysis of the second group of processes highlights that the transmission (process 8) accounts for 99.1% of the consumption of non-renewable resources. This is a result of the use of large concrete and steel-based structures to transmit energy for long distances, which are materials with high non-renewable resource consumption in their life cycles.

An in-depth analysis of the transmission process (8), shown in Fig. 7, reveals that the most consumed resources are sand, gravel,

Table 4
Consumption of non-renewable resources.

Process	Consumption of non-renewable resources (g/FU)	(%)
1	0.011	26.3
2	0.002	4.9
3	0.016	39.7
4	0.005	12.3
5	0.007	16.7
6	–	–
7	–	–
Total (1)	**0.041**	**100.0**
8	381.445	99.1
9	3.538	0.9
Total (2)	**384.983**	**100.0**

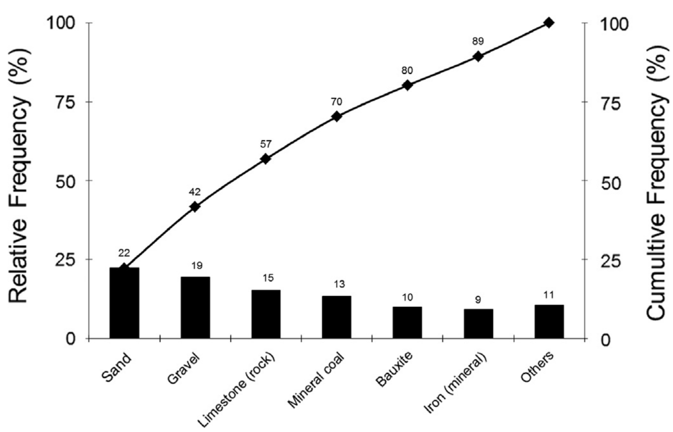

Fig. 7. Main non-renewable resources consumed in the electricity transmission process.

Table 5
Consumption of renewable resources.

Process	Consumption of renewable resources (g/FU)	(%)
1	0.887	7.5
2	0.073	0.6
3	0.596	5.1
4	0.019	0.2
5	–	–
6	8.680	73.7
7	1.529	13.0
Total (1)	11.784	100.0
8	895.002	99.5
9	4.948	0.5
Total (2)	899.950	100.0

limestone, mineral coal, bauxite and iron, representing 89% of the total resources consumed in this process.

4.2. Consumption of renewable resources

It can be clearly noticed in Table 5 that the processes of sugarcane washing and milling (6), energy cogeneration (7) and electricity transmission (8) are the major consumers of renewable resources. The processes 6 and 7 account for almost 87% of renewable resources consumption of the electricity generation phase, mainly water. Besides being used in large quantities in the sugarcane washing process, which is increased by the straw burning prior harvesting, large amounts of water are also needed in the $CaCO_3$ extraction process and sugarcane cultivation.

Table 6
Renewable inputs consumed in the process 8.

Inputs	Consumption of renewable resources (g/FU)	(%)
Water	889	91.4
Biomass	4	7.9
Air	2	0.4
Wood	0.002	0.2
Total	**895.002**	**100.0**

Table 7
Consumption of energy.

Process	Consumption of energy (g/FU)	(%)
1	–	–
2	0.116	−0.1
3	1.761	−1.0
4	0.183	−0.1
5	10.531	−5.9
6	64.973	−36.6
7	−255.038	−143.7
Total (1)	**−177.474**	**100.0**
8	565.000	85.5
9	95.997	14.5
Total (2)	**660.997**	**100.0**

In the electricity transmission and distribution cases, it is clear that the first presents, by far, the highest rate of consumption (99.5%). This can be explained by the high quantity of water (Table 6) that is employed in the resource extraction of materials to produce the transmission and distribution lines.

4.3. Consumption of energy

The results of the consumption of energy, mainly electricity, are shown in Table 7. Among the electricity generation processes (1–7), the processes 6 (sugarcane reception, washing and milling) and 5 (sugarcane harvesting) account for more than 97% of the energy consumed. This occurs because the large demand of the sugarcane milling process equipment's, which represents over 50% of the electricity requirements of the entire industrial process. It is interesting to notice that in the case of the electricity cogeneration process (7), there is a negative value of energy consumption because this process supplies the energy demand of process 6.

An additional analysis of the second group points out that the process 8 (electricity transmission) is the largest energy consumer (85.5%). This is attributable to the usage of steel and concrete in the transmission structures construction, which have very energy intensive processes.

4.4. Emissions

The emissions identified are presented in eight subsections according to the impact categories defined by the EDIP method – solid waste, global warming potential, ozone depletion potential, photochemical ozone potential, acidification potential, nutrient enrichment potential, ecotoxicity potential and human toxicity potential.

4.4.1. *Solid waste*

Tables 8–10 present the amount of solid waste generated by the product system studied separated by type – hazardous waste, bulk waste and radioactive waste – and process.

It can be clearly noted that amongst the electricity generation processes, the bulk waste is the major environmental impact potential caused mainly by silt (83.1%) generated in the sugarcane harvesting process (5), non-apatite waste (7.6%) from processes 2, 3 and 7 and ash (4.9%) from the sugarcane reception, washing and milling process. In the case of the hazardous waste, the chemical application (62%) and harvesting (30%) processes account for 92% of this type of waste generation. Divanadium pentoxide dreg (V_2O_5) from the P_2O_5 production is the main waste generated by the first process and lubricant residues are the major contributors in the harvesting process case. Finally, radioactive waste is not relevant in this group of processes.

Bulk waste is also the major environmental impact potential in the case of electricity transmission and distribution processes. In this case, the electricity transmission process accounts for 97.4% of the total bulk waste generated by this group, mainly due to high levels of non-inert production waste and residues generated in this process. In addition, in this group some hazardous waste – specifically inert waste from bauxite – is produced in the transmission process and no radioactive waste is generated.

Table 8
Generation of solid waste.

Process	**Solid wastes categories**					
	Bulk waste		**Hazardous waste**		**Radioactive waste**	
	(g/FU)	**(%)**	**(g/FU)**	**(%)**	**(g/FU)**	**(%)**
1	7.057	< 0.1	2.400E−04	< 0.1	2.070E−03	62.3
2	757.000	0.4	2.030	2.6	–	–
3	18,164.228	10.6	48.740	61.9	1.250E−03	37.7
4	–	–	–	–	–	–
5	143,000.000	83.1	23.700	30.1	–	–
6	8510.000	4.9	–	–	–	–
7	1626.000	0.9	4.344	5.5	–	–
Total (1)	**172,064.285**	**100.0**	**78.814**	**100.0**	**3.320E−03**	**100.1**
8	49.490	97.4	17.020	98.2	–	–
9	1.340	2.6	0.310	1.8	–	–
Total (2)	**50.830**	**100.0**	**17.330**	**100.0**	–	–

Table 10
Solid waste generated by the transmission and distribution processes.

Types of waste	**Processes (g/FU)**			
	8	**9**	**Total (2)**	**%**
Bulk waste	**49.490**	**1.343**	**50.833**	
Non-inert production waste	**27.000**	**0.060**	**27.060**	**53.2**
Residues	19.000	0.005	**19.005**	**37.4**
Solid waste	2.000		**2.000**	**3.9**
Unspecified inorganics	0.007	1.161	**1.168**	**2.3**
Inert production waste	1.000		**1.000**	**2.0**
Mineral waste	0.399	0.004	**0.403**	**0.8**
Unspecified waste	0.084		**0.084**	**0.2**
Cement blend's waste		0.066	**0.066**	**0.1**
Waste from cutting trees		0.045	**0.045**	**0.1**
Unspecified inert wast		0.001	**0.001**	**0.0**
Hazardous waste	**17.015**	**0.311**	**17.326**	
Inert waste from bauxite	17.000	0.309	**17.309**	**99.9**
Chemical waste	0.015	0.000	**0.015**	**0.1**
Aluminum slag		0.002	**0.002**	**0.0**
Lamination slag	0.000	0.000	**0.000**	**0.0**
Asbestos	0.000	0.000	**0.000**	**0.0**
Oil		0.000	**0.000**	**0.0**

Table 9
Solid waste generated by the electricity generation processes.

Types of waste	**Processes (g/FU)**							
	1	**2**	**3**	**5**	**6**	**7**	**Total 1**	**% Type**
Bulk waste	**7.057**	**757.000**	**18,164.228**	**143,000.000**	**8510.000**	**1626.000**	**172,064.285**	
Silt[d]				143,000.000			143,000.000	83.1
Non-apatite waste[c]		484.000	11,600.000			1040.000	13,124.000	7.6
Ash[d]					8510.000		8510.000	4.9
Magnetite[c]		145.000	3480.000			311.000	3936.000	2.3
Mud[c]		128.000	3080.000			275.000	3483.000	2.0
Unspecified solid waste[a]	5.400		3.230				8.630	0.0
Unspecified slag and ash, energy[a]	1.550		9.340E−01				2.484	0.0
Unspecified industrial waste[a]	9.780E−02		5.870E−02				1.565E−01	0.0
Mineral waste[a]	8.910E−03		5.350E−03				1.426E−02	0.0
Unspecified chemical waste[a]	3.420E−04		2.060E−04				5.480E−04	0.0
Non-inert product's waste[b]	4.340E−05						4.340E−05	0.0
Unspecified rubber[a]	6.290E−07		3.770E−07				1.006E−06	0.0
Unspecified slag and ash, incineration[a]	8.020E−09		4.810E−09				1.283E−08	0.0
Unspecified mud[a]	4.240E−13		2.550E−13				6.790E−13	0.0
Hazardous waste	**2.400E−04**	**2.030**	**48.740**	**23.700**	–	**4.344**	**78.814**	
Divanadium pentoxide dreg (V_2O_5)[c]		1.720	41.300			3.680	46.700	59.3
Lubricant[d]				23.700			23.700	30.1
Sulfur dreg[c]		0.310	7.440			6.640E−01	8.414	10.7
Unspecified hazardous waste[a]	2.400E−04		1.440E−04				3.840E−04	0.0
Radioactive waste	**2.070E−03**	–	**1.250E−03**	**–**	**–**	**–**	**3.320E−03**	
Unspecified nuclear waste[a]	2.070E−03		1.250E−03				3.320E−03	100.0

[a] Waste from the $CaCO_3$ extraction.
[b] Waste from trucks' diesel consumption.
[c] Waste from the P_2O_5 production.
[d] Residues.

Table 11
Global warming potential.

Process	Global warming potential (g CO_2-eq/FU)	(%)
1	2.195E−04	0.2
2	2.832E−03	2.4
3	5.354E−03	4.6
4	7.536E−04	0.6
5	0.108	92.1
6	–	–
7	1.035E−04	0.1
Total (1)	**0.117**	**100.0**
8	141.830	95.7
9	6.376	4.3
Total (2)	**148.206**	**100.0**

Table 12
Ozone depletion potential.

Process	Ozone depletion potential (g CFC11-eq/FU)	(%)
8	9.504E−06	97.7
9	2.256E−07	2.3
Total (2)	**9.729E−06**	100.0

4.4.2. Global warming potential

Table 11 presents the emissions that contribute to the global warming potential. Amongst the electricity generation processes, the sugarcane harvesting process (5) has the highest global warming potential accounting for 92.1% of the total of this kind of emission. This occurs due to the hydrocarbons gas, methane and carbon monoxide (CO) emitted during the straw burning before harvesting as well as the carbon dioxide (CO_2) emitted from the use of diesel oil in trucks and tractors. It is worth to notice that the CO_2 emissions from the straw burning are considered renewable resources as all CO_2 emitted to atmosphere return, in a cycle, to the sugarcane planted during the photosynthesis mechanism.

Another interesting point observed is the fact that the process 6 does not present any kind of global warming potential. This happens as the sugarcane bagasse is a kind of biomass, therefore, a renewable resource.

An analysis of the second group of processes, on the other hand, reveals that the electricity transmission is the major contributor to the global warming potential of the system in focus accounting for 95.70% of the total of this type of emissions. This can be explained by the fact that in the process 8 there are emissions of several substances with high global warming potential such as tetrafluoromethane (CF_4) and chlorofluorocarbons (CFCs) from the aluminum production, nitrous oxide (N_2O) from coke production, CO and CO_2 from concrete, steel, aluminum, copper, zinc and porcelain productions.

4.4.3. Ozone depletion potential

According to Table 12, emissions that affect the ozone depletion potential occur only at the electricity transmission and distribution phase, primarily at the former. The transmission process (8) is responsible for 97.7% of the total emissions of this kind. This can be explained by the fact that substances with high ozone impact potentials are emitted in this process, such as CFC's and carbon tetrachloride (CCl_4) emitted in the caustic soda production that is consumed in the aluminum production and the Halon 1301 used in the coke production.

Table 13
Photochemical ozone potential.

Process	Photochemical ozone potential (g C_2H_4-eq/FU)	(%)
1	1.045E−07	< 0.1
2	2.091E−07	< 0.1
3	4.181E−07	< 0.1
4	1.045E−07	< 0.1
5	4.447	99.9
6	–	–
7	2.091E−06	< 0.1
Total (1)	**4.447**	**100.0**
8	0.080	99.6
9	3.388E−04	0.4
Total (2)	**0.080**	**100.0**

Table 14
Acidification potential.

Process	Acidification potential (g SO_2-eq/FU)	(%)
1	2.091E−06	0.2
2	1.045E−06	< 0.1
3	6.272E−06	0.7
4	1.045E−06	< 0.1
5	8.331E−04	87.5
6	–	–
7	7.89E−05	11.4
Total (1)	**9.523E−04**	**100.0**
8	0.574	94.5
9	0.034	5.5
Total (2)	**0.608**	**100.0**

Table 15
Nutrient enrichment potential.

Process	Nutrient enrichment potential					
	(g N-eq/FU)	(%)	(g P-eq/FU)	(%)	(g NO_3-eq/FU)	(%)
1	6.272E−07	< 0.1	–	–	–	–
2	0.562	25.6	1.756E−04	3.6	–	–
3	1.054	48.1	4.223E−03	85.9	–	–
4	0.574	26.2	5.174E−04	10.5	–	–
5	4.181E−06	< 0.1	–	–	–	–
6	–	–	–	–	–	–
7	4.662E−05	< 0.1	–	–	–	–
Total (1)	2.191	**100.0**	4.916E−03	**100.0**	–	**100.0**
8	0.090	95.5	5.068E−06	99.8	5.712E−05	98.2
9	4.282E−03	4.5	1.121E−08	0.2	1.073E−06	1.8
Total (2)	**0.094**	**100.0**	**5.080E−06**	**100.0**	**5.819E−05**	**100.0**

4.4.4. Photochemical ozone potential

An analysis of Table 13 reveals that amongst the electricity generation processes, sugarcane harvesting (5) presents the highest rate of emission being responsible for almost 100.00% of the impact potentials of this group. This occurs as a consequence of the straw burning technique that is employed in the sugarcane harvesting process and the use of diesel oil in trucks and tractors.

In the second group of processes, on the other hand, it is observed that the electricity transmission process is the major contributor representing 99.58% of its impact potentials.

4.4.5. Acidification potential

An analysis of Table 14 shows that the sugarcane harvesting (process 5) presents the highest level of acidification potential among the electricity generation processes, mainly due to the

emissions of NO_x from the straw burning. Whereas in the second group, the electricity transmission (process 8) is the largest contributor for acidification potential due to the sulfur oxide emissions in the concrete, aluminum, zinc and porcelain productions.

4.4.6. Nutrient enrichment potential

The nutrient enrichment potential emissions are exposed in Table 15 separated in three types – nitrogen (N), phosphorus (P) and nitrate (NO_3) emissions. It can be clearly noted that among the electricity generation processes, the activities that incorporate soil nutrients are the major contributors, specially processes 3 and 4 (99%) due to the use of fertilizers and vinasse.

Once more, in the case of the second group of processes, the electricity transmission presents the highest nutrient enrichment potentials. It can be said that this happens mainly due to nitrate emissions from the usage of cyanide.

Table 16
Ecotoxicity potential.

Process	Ecotoxicity potential			
	Water		Soil	
	(m³/FU)	(%)	(m³/FU)	(%)
1	13.432	62.5	1437.171	0.2
2	4.181E−04	< 0.1	173,948.337	22.9
3	8.06	37.5	584,227.902	76.9
4	–	–	–	–
5	–	–	17.249	< 0.1
6	–	–	–	–
7	–	–	–	–
Total (1)	**21.493**	**100.0**	**759,680.659**	**100.0**
8	5.690	99.9	0.037	99.9
9	3.865E−03	< 0.1	5.491E−05	0.1
Total (2)	**5.694**	**100.0**	**3.691E−02**	**100.0**

Table 17
Human toxicity potential.

Process	Human toxicity potential					
	Air		Water		Soil	
	(m³/FU)	(%)	(m³/FU)	(%)	(m³/FU)	(%)
1	17,311.577	< 0.1	7.317E−02	2.4	6.690E−04	< 0.1
2	48,005.556	< 0.1	2.300E−02	0.8	7.317E−05	< 0.1
3	48,058.765	< 0.1	6.063E−02	2.0	1.725E−03	< 0.1
4	13,042.227	< 0.1	–	–	–	–
5	131,543,917.903	94.5	2.859	94.8	13,340.386	99.9
6	–	–	–	–	–	–
7	7,512,326.909	5.4	–	–	–	–
Total (1)	**139,182,662.937**	**100.0**	**3.016**	**100.0**	**13,340.388**	**100.0**
8	132,651.565	99.5	1.698	99.8	6.763E−03	98.9
9	604.862	0.5	2.927E−03	0.2	7.578E−05	1.1
Total (2)	**133,256.426**	**100.0**	**1.70**	**100.0**	**6.839E−03**	**100.0**

4.4.7. Ecotoxicity potential

The results of ecotoxicity potential are shown in Table 16 separated in water and soil ecotoxicity potentials. The analysis of the electricity generation process' group shows that its hydric ecotoxicity potential is caused mainly by the soil preparation (1) and chemical application (3) processes (99.99%) while its soil ecotoxicity potentials by the chemical applications (76.9%) by the latter. These impacts can be explained by the application of fertilizer and pesticides.

On the other hand, the electricity transmission process is accountable for the major impacts of the second group. This is a result of the residues from the production of transmission line components such as trace metals from concrete production and oil from converter production.

4.4.8. Human toxicity potential

Table 17 shows the results for human toxicity potential separated by compartment – air, water and soil. An analysis of the electricity generation processes reveals that the sugarcane harvesting (5) is the major contributor to human toxicity in all compartments. It can be said that the impact potentials via air and soil are due to the straw burning prior harvesting as well as the usage of diesel oil in trucks and tractors, and that the impact potentials via water occurs as a result of the usage of lubricant in harvesting machineries.

In the case of electricity transmission and distribution processes, it is clear that the first one is by far the major contributor to the human toxicity in all compartments. This happens as a consequence of the benzene emissions related to the coke production consumed in the steel production.

4.4.9. Normalization of the impact potentials

The previous section presented the impact potentials of each process at each environmental impact category not shedding light on the categories' comparative magnitude or on which of them decision makers should focus. In order to facilitate the main issues, a normalization process was carried out based on the EDIP

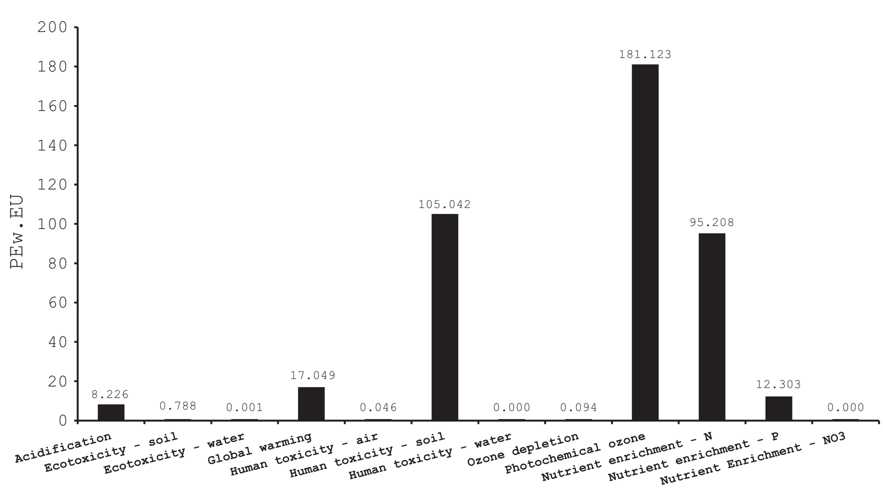

Fig. 8. Overall normalized emission potentials of the product system in focus.

Table 18
Normalized emission potentials by process (PEw.EU).

Category/unit process	1	2	3	4	5	6	7	8	9	TOTAL
Acidification	2.83E−05	1.41E−05	8.48E−05	1.41E−05	1.13E−02	–	1.47E−03	7.760	4.53E−01	**8.226**
Ecotoxicity – soil	1.49E−03	1.80E−01	6.06E−01	–	1.79E−05	–	–	3.82E−08	5.70E−11	**0.788**
Ecotoxicity – water	4.62E−04	1.44E−08	2.77E−04	–	0.00E+00	–	–	1.96E−04	1.33E−07	**0.001**
Global warming	2.52E−05	3.25E−04	6.15E−04	8.66E−05	1.24E−02	–	1.19E−05	16.302	7.33E−01	**17.049**
Human toxicity – air	5.66E−06	1.57E−05	1.57E−05	4.26E−06	4.30E−02	–	2.46E−03	4.34E−05	1.98E−07	**0.046**
Human toxicity – soil	5.27E−06	5.76E−07	1.36E−05	–	1.05E+02	–	–	5.33E−05	5.97E−07	**105.042**
Human toxicity – water	1.40E−06	4.41E−07	1.16E−06	–	5.48E−05	–	–	3.25E−05	5.61E−08	**0.000**
Ozone depletion	–	–	–	–	–	–	–	9.23E−02	2.19E−03	**0.094**
Photochemical ozone	4.18E−06	8.36E−06	1.67E−05	4.18E−06	177.894	–	8.36E−05	3.215	1.36E−02	**181.123**
Nutrient enrichment (N)	2.61E−05	23.414	43.937	23.937	1.74E−04	–	1.94E−03	3.740	1.78E−01	**95.208**
Nutrient enrichment (P)	0.00E+00	4.39E−01	10.557	1.294	0.00E+00	–	–	1.267E−02	2.80E−05	**12.303**
Nutrient enrichment (NO_3)	–	–	–	–	–	–	–	4.80E−04	9.01E−06	**0.000**
Total	**2.05E−03**	**24.034**	**55.101**	**25.231**	**283.003**	–	**5.96E−03**	**31.123**	**1.380**	

Method. The results are presented in Fig. 8 and Table 18 expressed in person-equivalents (PEw.EU) or as a fraction of the annual average impact potentials of a European citizen, as explained in Section 3.3.

A comprehensive analysis of Fig. 8 shows that the categories can be divided into three main groups: high, medium and low impact potentials. The first group that should be the primary focus of decision makers as they represent by far the highest comparative impact potentials encompasses the photochemical ozone, human toxicity via soil and nutrient enrichment (N) impacts. The photochemical ozone impact category has a normalized score of 181.123 PEw.EU, while the human toxicity via soil 105.042 PEw.EU and the nutrient enrichment (N) 95.208 PEw.EU.

A more in-depth analysis of these categories shown in Table 18 reveals some causes of this performance. It can be seen that the photochemical ozone and human toxicity via soil impact potentials are primarily generated by the sugarcane harvesting process since this set of activities is accountable for more than 98% of the total normalized impact potentials of these two categories. The main causes of both categories' high impact are the air emissions of CO (99%) and dust from the straw burning prior harvesting and the use of diesel oil in trucks and tractors. On the other hand, nutrient enrichment (N) potentials are caused mainly by the chemicals application – the use of fertilizers and vinasse application in processes 2, 3 and 4.

A second group of priorities encompasses global warming, nutrient enrichment (P) and acidification impacts with the following scores: 17.049 PEw.EU, 12.303 PEw.EU and 8.226 PEw.EU. An in-depth analysis of Table 16 shows that the transmission process is the major contributor for the global warming and acidification impact potentials. In the first case, it accounts for more than 95% of global warming total impact potentials which are caused by emissions of several substances with high global warming potential such as tetrafluoromethane (CF_4) and chlorofluorocarbons (CFCs) from the aluminum production, nitrous oxide (N_2O) from coke production, CO and CO_2 from concrete, steel, aluminum, copper, zinc and porcelain productions. On the other hand, acidification potentials in this process occur mainly due to sulfur oxide emissions in the concrete, aluminum, zinc and porcelain productions.

Moreover, the chemical application process is responsible for 85.8% of the nutrient enrichment (P) impact potentials. This is caused mainly by the use of fertilizers and vinasse application.

Finally, a third group encompasses all other categories with scores lower than 1.000 PEw.EU.

5. Conclusion

This study aimed to identify and quantify the environmental impact potentials of the sugarcane bagasse electricity system to highlight its main environmental improvement opportunities. An analysis of the results shown in Section 4 reveals two key sets of environmental impacts – emissions and resource consumption.

Regarding to the environmental emissions, one can conclude that governmental and industry decision makers should focus on addressing photochemical ozone, human toxicity via soil and nutrient enrichment emissions from the sugarcane harvesting and chemical application processes. The main causes of the first two are the straw burning prior harvesting, primarily, and the use of diesel in trucks and tractors for harvesting. Thus, the substitution of this technique is fundamental. In this sense, the Sao Paulo State government, where the majority of the sugarcane ethanol industries are based, has already established a law to reduce the usage of such a technique. This means that this type of impact potentials will be reduced in a near future in Brazil.

The elimination of straw burning would bring some other benefits as well. First of all, a decrease in the global warming impact potentials due to the elimination of the hydrocarbons gas, methane and carbon monoxide that are emitted from this activity. Second, there would be a reduction in the consumption of renewable resources, namely water, since the burnt sugarcane is dirtier than the green one requiring a larger amount of water in the washing process. Moreover, the sugarcane straw could be used to generate more electricity to be exported to the grid and/or could be left in the field to improve soil conditions, reducing chemicals application.

On the other hand, to improve the nutrient enrichment potentials (N) some process changes in the chemicals application process are fundamental. These improvements should regard the reduction and the type of fertilizers used and vinasse as well as the implementation of pollution prevention activities.

The consumption of non-renewable resources, renewable resources and energy are also important environmental aspects to be addressed. In the case of non-renewable resources, the major potential consumption lies on the transmission process mainly regarding the sand, gravel, limestone, mineral coal and bauxite consumptions. Thus, an in-depth analysis of this process and the large structures necessary to transmit energy for long distances is fundamental. From the renewable resources and energy consumptions points of view, water and energy consumptions in the electricity transmission and sugarcane reception, washing and milling processes are the main points to be addressed. In this sense, the implementation of eco-efficient actions aiming the optimization of the resource usage is critical.

Finally, this study is not free of limitations. The major one is the fact that around 19% of the product system in focus total emissions, which were related to waste water from the alumina process, were disregarded because the EDIP method does not

encompasses this kind of emission. Additionally, the restricted access to details of the electricity transmission and distribution processes limited in part the cause analysis of these processes' impacts. Therefore, it is advised that more in-depth analysis of these processes be carried out to identify the major causes, thus, defining more effective actions.

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